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Translations of Soviet-Bloc Scientific and Technical Literature

PRODUCING POWERFUL RADIO PULSES BY THE ELECTRIC EXPLOSION OF METAL WIRES

Translation

ATD Work Assignment No. 79
Task 32

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FOREWORD

This translation was prepared in response to Work Assignment No. 79, Task 32. The article was originally published as follows:

Kul'gavchuk, V. M. Polucheniye moshchnykh radioimpul'sov pri pomoshchi elektricheskogo vzryva metallicheskih provolok. Pribory i tekhnika eksperimenta, no. 1, 1965, 132-137.

PRODUCING POWERFUL RADIO PULSES BY THE ELECTRIC EXPLOSION OF METAL WIRES

An investigation is made of impact excitation of a parallel oscillating circuit, connected in series with wires "exploded" by a high-density current. Copper and silver wires 0.04—0.1 mm in diameter and 1.5—2.5 cm long were used as switching elements. It is shown that given a discharge potential of 4.5—7 kv and a storage capacity of 0.58 to 0.77 μ f, weakly damped (logarithmic damping decrement of $3-6 \times 10^{-2}$) oscillations are generated during the current pause, characterized by currents of the order of 10^2-10^3 amp and frequency within the range from 2.6 to 29 Mc/sec. The dependences of initial excitation amplitude on the number and diameter of the exploding wires, on the discharge potential, and on the natural frequency of the circuit show that the initial amplitude increases with a decrease in wire diameter and decreases with an increase in frequency according to a law close to $1/\omega^2$. A method is given for evaluating the initial amplitude of the oscillations.

Reference [1] shows that a capacitor discharging through a series-connected metal wire and oscillator results in an impact excitation of powerful oscillations whose damping is several times weaker than in the well known method of discharging the capacitor through a spark gap and an inductance. Such oscillations may find application in experimental physics for helical scanning to measure time intervals with oscillographs and for image converters, especially when recording single phenomena. Similar oscillations can be used to modulate the light transmitted by a Kerr cell to provide a time base. Finally, such oscillations are necessary in experiments with plasma for the creation of the θ -pinch. The aim of this work is to determine the dependence of initial oscillation amplitude on parameters of the discharge circuit, on the size of the switching element (wires), on the discharge voltage, and on the natural frequency of the oscillating circuit.

Without dwelling on the details of the electric explosion phenomenon, which can be found in various works [2, 3], let us investigate the mechanism of impact excitation of an oscillating parallel circuit when a current pause is formed (Fig. 1). After the discharger P is switched on, an increasing current begins to flow through the wire II and the oscillating circuit. At a current density in the wire $> 10^7$ amp/cm² the wire in a time period of $10^{-8}-10^{-7}$ sec [2] is transformed into a cylinder of over-compressed nonconductive vapors, and as a result, the so-called current pause forms in the discharge circuit. Furthermore, during the time of the current pause the oscillating circuit which has accumulated a magnetic energy $1/2 L_K I^2$ (where L_K is the inductance of the oscillating circuit and I is the current before switching off) will be switched off from the discharge circuit, after which damped oscillations will appear in it.

As will be shown, the value of the derivative of current during switching-off will determine the magnitude of the initial oscillation amplitude.

Fig. 2 shows a pulse of current derivative in the discharge circuit when the oscillating circuit is shunted out; the width of its negative section at the base is equal to the switch-off time. As can be seen from the

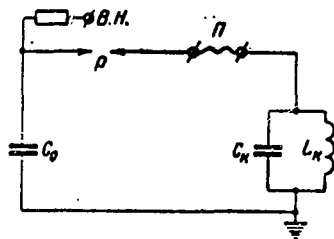


Fig. 1. A schematic diagram of the switching on of the oscillating circuit into a discharge circuit

P - Air discharger; Π - wire;
B.H. - high voltage.

picture, the positive pulse section, after a rapid increase during the time in which the breakdown is developing in the discharger beyond t_p , becomes constant for some time, and subsequently monotonically increases in steepness

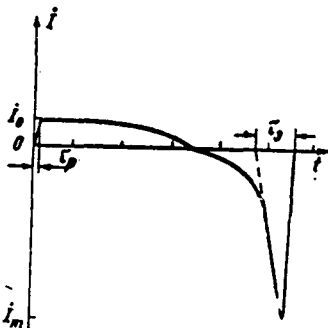


Fig. 2. A schematic representation of the current derivative oscillogram in a discharge circuit obtained with an explosion of four copper wires 0.04 mm in diameter and 2.5 cm long connected in parallel at $V_0 = 6.1$ kv, $L_0 = 0.24$ μ h, $C_0 = 1.08$ μ f. Marks on the time-axis represent 0.1- μ sec intervals

and passes into a negative section, which ends with a section in which there is almost a linear increase accompanied by extreme steepness.¹

Fig. 3 shows dependences of the ratio of derivatives i_m/i_0 on the discharge voltage for switching elements of equal cross section but consisting of one and four wires. The dependences were obtained in discharge circuits with different inductances L_0 and capacities C_0 . From these data it is seen that this ratio increases with the rise of the discharge voltage and circuit inductance, and with the decrease in the wire diameter.

At a pulse current duration τ considerably smaller than one-fourth of the oscillation period, the initial amplitude is determined by the relationship

$$u = \omega \rho \int_0^{\tau} I(t) dt,$$

¹A weak break in the current derivative appears with the melting of the wire; in Fig. 2 it coincides with the moment when i passes zero.

where ω is the frequency of natural oscillations and ρ is the wave impedance of the circuit. With the decrease of the T period the initial amplitude will increase and will reach a maximum when the pulse duration is close to one-half of the period. With a further decrease of the period, when its quarter becomes shorter than the current pulse, the initial amplitude will start decreasing. In the first approximation it can be

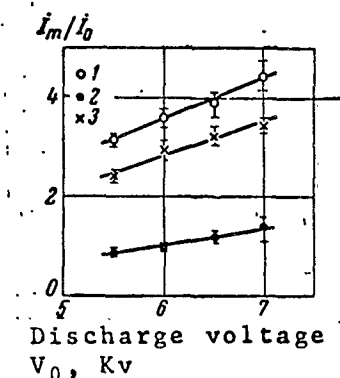


Fig. 3. Dependence of i_m/i_0 on discharge voltage for copper wires 2.5 cm long

1 - Four parallel wires 0.04 mm in diameter, $L_0 = 0.24 \mu\text{h}$, $C_0 = 0.77 \mu\text{f}$; 2 - the same specimen, $L_0 = 0.1 \mu\text{h}$, $C_0 = 0.58 \mu\text{f}$; 3 - one wire 0.08 mm in diameter, $L_0 = 0.24 \mu\text{h}$, $C_0 = 0.77 \mu\text{f}$.

assumed that in this case the excitation of oscillations will occur twice—during switching-on of the discharger and during switching-off of the current. Owing to the linearity of the system, the resulting amplitude will be a superposition of the oscillations from these two impacts. In addition, the circuit after the first impact will be shunted with elements of the discharge circuit, while after the second impact it will be switched off from the discharge circuit, and only the appearance of a secondary discharge between the wire terminals will cause it to shunt.

Let us evaluate the initial excitation amplitude, assuming that the time for switching-off the current is greater than one-fourth of the oscillation period. The oscillograms (Fig. 4) show that the circuit is excited at the moment of a sharp increase (in absolute magnitude) of the current derivative; let us assume that the increase during this time is linear $\dot{i} = \dot{i}_m + t/\tau_3$. Here \dot{i}_m is the maximum value of current derivative during switch-off, and τ_3 , which we will call effective time of current switch-off, will represent an interval on the time axis between the point where the axis intersects the line drawn by extrapolating the linear section of \dot{i} and the pulse end (Fig. 2). The dependence of τ_3 on discharge voltage for switching elements consisting of wires 0.08 and 0.04 mm in diameter can be obtained from Fig. 5.

Let us assume that the circuit has a sufficiently high Q ($Q \gg 1$), which will permit us to disregard the effect of damping on the initial amplitude. The equation will be written as:

$$C_n \frac{du}{dt} + L_n^{-1} \int u dt = I(t).$$

After differentiating we will have

$$d^2u/dt^2 + \omega^2u = \dot{I}(t)/C_K,$$

where $\omega = 1/\sqrt{L_K C_K}$. Assuming that $\dot{I} = I_m t/\tau_0$ and taking into account only the coefficient at the harmonic term, the solution of the equation will have the following form:

$$u = I_m \rho / \tau_0 \omega^2,$$

where $\rho = \sqrt{L_K/C_K}$.

The described picture of circuit excitation can be qualitatively traced on the oscillograms in Fig. 4, where the voltage on the oscillating circuit for different circuit parameters is shown. Here the oscillations excited

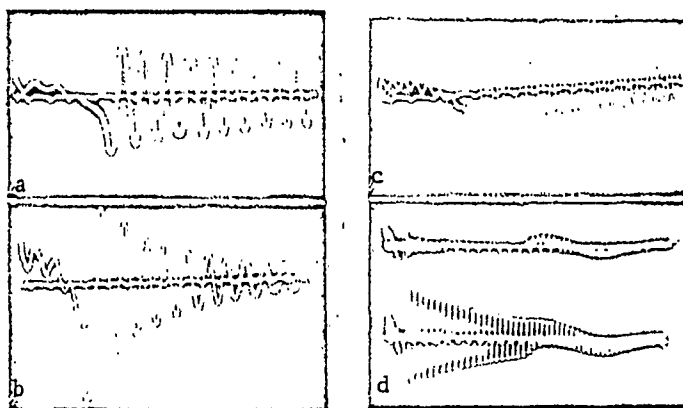


Fig. 4. Oscillograms of excited oscillations:

a - $f = 8.9$ Mc/sec, $u = 4.1$ kv; b - $f = 8.9$ Mc/sec, $u = 5.7$ kv (circuit is shunted with a 39-ohm resistance); c - $f = 16.9$ Mc/sec, $u = 3$ kv; d - $f = 9.7$ Mc/sec, $u = 2.9$ kv (the upper beam shows the current derivative in a discharge circuit). Time markings: a, b, c - after 0.1 μ sec; d - after 0.2 μ sec.

during switching-on of the discharger and during switching-off of the current can be seen clearly; the first ones occur at the beginning of the sweep; the second ones after 0.2—0.3 μ sec.

During the current pause, a voltage representing the sum of the high-frequency voltage and the voltage remaining on the capacitor after the breakdown of the circuit is applied to the exploding wire terminals. Since the high-frequency voltage diminishes with time, the total voltage appears

to be highest at the moment of current pause formation. If $1/4 T \ll \tau_0$,

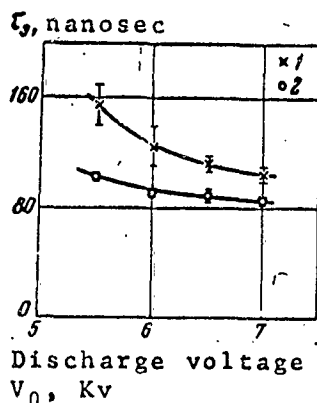


Fig. 5. Dependence of the effective time of current switch-off with copper wires 2.5 cm long on discharge voltage, $L_0 = 0.24 \mu\text{h}$, $C_0 = 0.77 \mu\text{f}$

1 - One wire 0.08 mm in diameter;
2 - four wires 0.04 mm in diameter.

then the first half-period of oscillations (negative) will be considerably larger than the initial amplitude (Fig. 4, c) since it is the pulse of the overvoltage appearing on the inductance of the circuit during the switch-off of the current and is equal to $L_0 i_m$. When the exploding wire is shortened, the high-frequency voltage and the residual voltage increase, resulting in shortening of the current pause. Before the radio-pulse ends a secondary discharge appears in the vapor of the scattered metal. From the moment of the appearance of the discharge, the oscillation amplitude decreases and characteristic distortions appear (Fig. 4, d). With a further shortening of the exploding wire or with an increase in the stored energy, the wire is shunted by a discharge at the moment of the formation of the current pause, and as a result the radio-pulse is absent. In selecting the length of the exploding wire, the fact that the duration of the current interval is longer when thin wires are used than when thick wires are used, should be taken into consideration.

To verify the conclusions, experiments were performed on the excitation of the oscillating circuit² $L_K = 29 \text{ m}\mu\text{h}$, $C_K = 11,250 \mu\text{f}$, $f = 8.9 \text{ Mc/sec}$, and $\rho = 1.6 \text{ ohm}$ in a discharge circuit with $L_0 = 0.24 \mu\text{h}$ and $C_0 = 0.77 \mu\text{f}$. Table 1 gives the dependence of the initial amplitude of excitation (the average of three experiments) on the discharge voltage V_0 for different commutators consisting of 2.45-cm-long copper wires. The amplitude of the second

²The oscillating circuit consisted of two 14 x 20 x 1 mm copper plates located 3.7 cm from each other, between which 20 КОБ-2 capacitors of 500 μf each were placed in 5 rows (4 capacitors in each row); from the narrow side between the plates a connecting link made of the same material was installed.

half-period was taken as an initial amplitude.³ The Q of the circuit under these conditions varied from 55 to 80 (logarithmic damping decrement $\theta = 3.9 \times 10^{-2} - 5.7 \times 10^{-2}$).

Table 1

Wire diameter, mm	No. of exploding wires	Initial amplitude, kv				
		$V_0 = 5.0$	$V_0 = 5.5$	$V_0 = 6.0$	$V_0 = 6.5$	$V_0 = 7.0$
0.04	5	1.5 ± 0.3 0.4	2.1 ± 0.1 0.2	3.1 ± 0.6 1.1	3.8 ± 0.1	4.1 ± 0.2
0.04	4	1.9 ± 0.2 0.1	2.4 ± 0.1 0.2	2.9 ± 0.1	3.1 ± 0.2 0.3	3.7 ± 0.2 0.1
0.08	1	0.8 ± 0.3 0.2	1.2 ± 0.2 0.1	1.8 ± 0.4	2.2 ± 0.2	2.7 ± 0.1 0.3
0.07	1	1.0 ± 0.2	1.2 ± 0.2 0.1	2.1 ± 0.2 0.1	2.2 ± 0.2 0.3	2.3 ± 0.4 0.3
0.05	2	1.3 ± 0.1	2.1 ± 0.1 0.2	2.3 ± 0.2	2.5 ± 0.3 0.2	3.5 ± 0.2 0.3
0.04	3	1.1 ± 0.3	1.8 ± 0.3	2.2 ± 0.3 0.4	2.8 ± 0.5 0.3	3.5 ± 0.1 0.2

From the table it can be seen that the initial amplitude at the same cross section of the switching element increases with the number of wires in it, since this leads to an increase of i_m and a decrease of V_0 . The considerable spread of initial amplitude observed in the experiments under equal conditions can be explained by the fact that the amplitude represents a superposition of the oscillations from two impacts, and that the amplitude of the oscillations from the first impact, as is seen from the oscillograms, is within the limits 0.1—0.5 μ ; therefore, a small fluctuation of the beginning moment of the sharp increase of I provokes a considerable change in the phase differences of the investigated oscillations.

Table 2 gives initial amplitude (averaged from four experiments) and oscillation power $W = u^2/2\rho$ for circuits with natural frequencies from 2.56—28.8 Mc/sec at a voltage $V_0 = 7$ kv in a discharge circuit with the same parameters as found in the experiments of Table 1 with the same commutator — in four copper wires 0.04 mm in diameter and 2.45 cm long connected in parallel. The values of the initial amplitude calculated from relationship (1) and data from Figs. 3 and 5 are given in the last column of Table 2.

³ To measure the voltage on the circuit, a voltage divider with a total resistance of 1.4—3.7 kohm was used.

As is seen from the table, the calculated data coincide with experimental values within an order of magnitude (except for one case in which the calculated data appeared to be lower).

Table 2

Circuit capacity $C_K, \mu\text{F}$	Circuit inductance L_K, mH	Frequency $f, \text{Mc/sec}$	ρ, ohm	$\theta \times 10^2$	Initial amplitude, kv		Oscillator Power, Mw
					Experiment	Calculated	
18300	210	2.56	3.4	3.0	$5.5 \pm 0.3^*$	—	4.45
11250	29	8.9	1.6	5.3	3.7 ± 0.2 0.1	0.81	4.27
1620	87.5	13.3	7.34	3.62	1.7 ± 0.3 0.2	1.64	0.197
1100	87.5	16.9	9.3	4.16	2.4 ± 0.6 0.8	1.32	0.31
560	73	24.8	11.4	5.6	1.0 ± 0.13 0.17	0.71	0.044
560	35	28.8	9.9	3.5	0.37 ± 0.12	0.47	0.0069

*Discharge voltage V_0 in this experiment was not 7 kv, as in the other experiments given in this table, but was only 4.3 kv. This was because at $V_0 > 4.5$ kv breakdown between the exploding wire holders took place due to the high value of the initial amplitude.

The results of excitation of a circuit $L_K = 29 \text{ mH}$ and $C_K = 11250 \mu\text{F}$ (average of three experiments) in a discharge circuit with a relatively small inductance $L_0 = 0.1 \mu\text{H}$ and $C_0 = 0.58 \mu\text{F}$ are given in Table 3; Table 4 shows the initial amplitude of the oscillating circuit shunted with a 39-ohm resistance and the power of oscillations at $V_0 = 7$ kv; Fig. 4b gives the oscillogram of the pulse.

Table 3

Metal	Wire diameter, mm	Length of wire, cm	No. of exploding wires	Initial amplitude, kv		
				$V_0=6$	$V_0=6.5$	$V_0=7$
Copper	0.05	2.5	4	2.4 ± 0.2	5.0 ± 0.3 0.2	5.4 ± 0.1
Copper	0.04	2.0	6	4.2 ± 0.6 0.4	6.0 ± 0.5	$6.8 \pm 0.4^*$ 0.5
Silver	0.1	2.5	1	2.8 ± 0.3 0.2	5.3 ± 0.4	$5.8 \pm 0.2^{**}$ 0.3

*Radio pulse discontinues after ~ 2 sec due to the appearance of a secondary discharge.

**Breakdowns occur between the exploding wire holders during the formation of the current interval.

The measurements show that when the circuit is shunted with a 39-ohm resistance, its quality factor decreases from 60 to 17, and maximum current in resistance reaches 150 amp. A comparison of the data in Tables 1 and 3 proves that the initial amplitude increases with the decrease in inductance of the discharge circuit because of the increased portion of the usable magnetic energy of the discharge circuit.

Table 4

Metal	Wire diameter, mm	Wire length, cm	No. of exploding wires	Initial amplitude, kv	Oscillator power, Mw	Remarks
Copper	0.04	2.0	6	5.4 ± 0.3 5.4 ± 0.4	9.1	Average of 6 experiments
Copper	0.04	1.5	6	6.0 ± 0.4 6.0 ± 0.5	11.2	Average of 7 experiments
Silver	0.1	2.5	1	4.4 ± 0.2	6.06	Average of 9 experiments

Table 2 shows that the transfer of energy from capacitor C_0 to the circuit reaches 3.2% (circuit with $f = 2.56$ Mc/sec).

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